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Item Type	Article
Authors	Folorunso, Oladipo;Hamam, Yskandar;Sadiku, Rotimi;Kupolati, Williams
Publisher	Springer
Rights	Attribution-NonCommercial-ShareAlike 4.0 International
Download date	2026-06-11 00:35:13
Item License	http://creativecommons.org/licenses/by-nc-sa/4.0/
Link to Item	https://hdl.handle.net/20.500.14519/2124



Effects of Defects on the Properties of Polymer Nanocomposites: A Brief Review

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Received: 23 May 2024 / Accepted: 6 June 2024 / Published online: 16 July 2024
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Abstract

Polymer nanocomposites are promising materials for various applications in the electronics, biomedicine, and aerospace industries. However, the fabrication errors or defects, e.g., induced porosity, significantly impact the performance and the reliability of devices fabricated from polymer nanocomposites. Hence, this study has comprehensively carried out an investigation into the effects of defects on the properties of photovoltaic active cells, biomimetic scaffold, and aircraft structures that are fabricated by using polymer nanocomposites. Agglomeration is another defect that degrades the intended properties of polymer nanocomposite devices. For photovoltaic devices, defects can be controlled by the selective modification of organic semiconductor molecular structures. In addition, proper optimization of the process parameters and the material selection, are effective approaches for obtaining excellent photovoltaic cells. Furthermore, the presence of impurities, a non-homogeneous mixture of organic and inorganic materials, and the incomplete solubility of nanoparticles, are detrimental factors that affect the cell proliferation performance of biomimetic scaffolds. These technological imperfections must be also avoided when producing parts for aircraft structures. In other words, impurities introduced during the synthesis or processing stages can lead to irregularities in the material structure, which often affect its mechanical, electrical, biomedical, and optical properties. The understanding and mitigating of these factors are crucial for the optimization of the properties and performance of polymer nanocomposites in various applications.

Keywords Defects · Polymer nanocomposites · Biomimetic scaffolds · Photovoltaic cells · Aircraft structures

1 Introduction

Very essential to the functionality of materials, are their properties. That is, the characteristics and attributes or properties, such as: mechanical strength, electrical conductivity,

bioactivity, chemical stability, and electrical conductivity of materials, have direct impact on the material's specific tasks and functions. Therefore, the optimization of material's properties, are critical for the design and engineering of the materials, towards a particular application [1].

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A porous nanocomposite has a proportional impact on the electrical conductivity of the material. However, defects due to induced porosity, often result into a low mechanically inviable material [2]. Therefore, the question of how to fabricate smart polymer nanocomposites for self-sensing and adaptability, is crucial for urgent answers. A smart polymer nanocomposite can be porous and still provide the desired electrical and mechanical properties. It has often, been reported that the toughness of a material can be reduced by its residual porosity; and porosity can result in anisotropy of the material in question [3]. An anisotropic material is a material that is characterized with different properties in different directions. In addition, polymer nanocomposite porosity effects, may be advantageous to some device applications, while on the other hand, it may be deleterious to some device functionalities. Induced porosity, due to the fabrication process, may lower the stiffness and mechanical strength of polymer nanocomposites. However, to some degree, porosity is advantageous to scaffolds for tissue and membranes engineering. Hence, it is imperative to comprehensively, re-examine the defect or porosity effects on polymer nanocomposites for different device applications.

Nevertheless, the extrinsic porosity in polymer nanocomposites, depends on several factors, which may include:

- a) Nanofiller type,
- b) Process technique,
- c) Synthesis time,
- d) Temperature,
- e) Solvent type,
- f) Compatibility of the filler and polymer matrix and
- g) Equipment and process control.

The study presented by Thabet and Ednalwaled [4] on enhancing the surface energy properties of polyvinylchloride-based nanocomposites, demonstrated that the type and volume concentration of nanoparticles are crucial factors influencing the properties (such as: contact angles and interfacial interaction energy) of polymer nanocomposites. The electrical properties of polymer nanocomposites, such as dielectric properties, can be varied based on the types of fillers and matrices used, as well as the volume concentration of the filler [5]. In addition, defect magnitude and surface functionalization can potentially alter the electrical and mechanical properties of materials [6].

A homogeneous dispersion of fillers in the matrix of polymer, will create perfect interaction between the filler and the polymer, which would lead to an excellent material, possessing enhanced mechanical, electrical, chemical, thermal, and optical properties [7]. For some polymer nanocomposites, at low filler volume fraction of the filler in polymer matrix, void spaces in the polymer-filler system may be perfectly filled due to low or negligible agglomeration or intercalation

in the nanocomposite system. In this regard, the intrinsic porosity of the materials is preserved, and the filler acting as reinforcement. Hence, the mechanical property of the nanocomposite will be enhanced. However, additional, or unwanted porosity can be created in the nanocomposite when the filler volume fraction increases to the point where the filler begins to agglomerate or intercalate to create voids or pores—this effect is a consequential trade-off of the mechanical integrity of the nanocomposite. Therefore, porosity, which is directly related to the material's compactness, must be effectively controlled for optimal performances of polymer nanocomposite devices. The agglomeration in polymer/metal-based nanocomposites for photovoltaic applications, can be reduced by employing an appropriate synthesis method. For instance, during the experimentation, carried out by Tay et al. [8], on the fabrication of polymer/metal nanocomposite for silicon photovoltaic cell, it was observed that self-assembly by immersion technique, is more suitable than dip coating technique. The polymer/metal nanocomposites coated on the silicon solar module by self-assembly immersion techniques, yielded 42% and 73.6% power conversion efficiencies. The enhancement in the polymer nanocomposite photovoltaic performance, can be attributed to the homogeneity of the polymer nanocomposites coated on the silicon-surface.

In the predictive study conducted by Ha et al. [9], graphite-nanoflake/polydimethylsiloxane nanocomposite was prepared by using solvent casting, hand lay-up, and the spray lay-up techniques. Oftentimes, the fabrication methods of polymer nanocomposites are the leading factors responsible for the nanocomposites' effective properties. Ha et al. reported that between the solvent casting, hand and spray lay-up methods, the spray lay-up technique created the smallest void in the graphite-nanoflake/polydimethylsiloxane nanocomposites. Nevertheless, with the increasing concentration of graphene-nanoflakes in the polymer matrix, the porosity of the nanocomposites also increased. The generated/induced porosity, resulted into the negative alteration of the elastic modulus, fracture strength, and elongation-at-break of the nanocomposites. By using some mathematical equations, Alasfar et al. [10], objectively investigated the response of the mechanical properties of polymer nanocomposite with respect to porosity. The polypropylene/nanoclay nanocomposite, showed a decrease in its elastic modulus due to the presence of residual porosity. Moreover, the yield stress of the nanocomposite decreased with an increase in the nano-clay filler volume fraction.

Referring to the study conducted by Elahi et al. [11], the effect of titanium dioxide on the tensile modulus of polyaniline conjugated polymer, showed an incremental behavior as the weight fraction of the filler increased. However, the non-linearity behavior of the filler effect on the mechanical tensile property of the nanocomposite depicted how the

nanocomposite became saturated as the filler concentration kept increasing. This scenario also explained the fact that, to modify the properties of polymer, the filler concentration must be kept at a minimum or at the percolation threshold of the material in question. The contribution of graphene and carbon-nitride nanoparticles on the mechanical properties of poly(3-hexylthiophene), were presented in the exploratory study conducted by Zhang et al. [12]. The result of the study showed that as the graphene concentration increased in the poly(3-hexylthiophene) matrix, the elastic modulus of the nanocomposites increased. This result was attributed to the uniform dispersion of graphene in the polymer matrix. Similarly, the strong interfacial interaction between the graphene nanoparticles and the polymer matrix promotes the mechanical reinforcement of the nanocomposites. Conversely, the carbon-nitride/poly(3-hexylthiophene) nanocomposites showed a low mechanical integrity as the concentration of carbon-nitride nanoparticles increased in the polymer matrix. The low mechanical integrity of the nanocomposite may be because of the complex interactions between the nanoparticles and the polymer matrix, which caused nanovoids within the nanocomposite.

Generally, the agglomeration of nanofiller within polymer nanocomposite is not a desirable occurrence; it degrades the intended properties of nanocomposites. In Tamayo-Vegas et al. [13], experimentation and theoretical studies of the effects of agglomeration on the electrical and mechanical properties of a multi-walled-carbon-nanotube/epoxy (MWCNT/epoxy) nanocomposite, it was noted that the influence of agglomeration on the samples prepared, began at 2% volume fraction of the filler inclusion. At the initial stage, when the volume fraction of MWCNT in the matrix of the epoxy was low, the elastic modulus of the nanocomposite experienced a positive enhancement. Nevertheless, due to agglomeration and porosity, the mechanical strength of the nanocomposite decreased as the filler concentration increased. The electrical conductivity of the fabricated material, behaved in the same manner as the mechanical strength. However, the electrical conductivity still experienced non-negligible linear incremental steps, until the saturation point was reached. In addition, a silver/thermoplastic-elastomer nanocomposite, produced by the batch-mixing technique, showed a low resistivity at its percolation threshold [14]. The nanocomposite agglomerated at high concentration of silver nanoparticles in the thermoplastic-elastomer matrix. The agglomeration resulted in high resistivity as it increased with increasing silver-nanoparticles concentration.

This study aims to present polymer nanocomposite's defect/porosity effects, on its: electrical, mechanical, and biomedical properties. The properties of photovoltaic, tissue engineering, and aerospace applications of polymer nanocomposites, are succinctly discussed. The review found out that defects can be advantageous, and in some instances,

they can also be deleterious. While porosity is a significant effect in biomimetic scaffold, it can be very detrimental to the desired performances of photovoltaic active layer, and aircraft parts. This study suggests the thorough optimization of the synthesis parameters and the appropriate choice of compositing materials for specific applications.

2 Polymer Nanocomposites for Electronic Applications

The expanse of polymer nanocomposites for electronic applications can be linked to the synergistic contributions of the facile processability, electrochemical, elasticity, ductility, dielectric properties of polymers, and the inorganic materials thermal, electrical, electrochemical, mechanical, optical, and electromagnetic properties [15–17]. For electronic applications, polymer nanocomposites have been considered as excellent materials for the fabrication of organic-light-emitting-diodes, photovoltaics, photo-detectors, transistors, sensors, optocoupler, and electro-chromic devices [18]. Amongst others, examples of polymers with electronic characteristics, include: polypyrrole, polythiophene, polyaniline, and poly(3,4-ethylenedioxythiophene)/polystyrene-sulphonate. Graphene, graphene-oxide, borophene, reduced-graphene-oxide, metals nanoparticles, and quantum dots, are examples of nanofillers for polymer nanocomposites. The electrical, charge-carrier mobility, and optical absorption materials are unique properties of these materials. The effects of defect/induced porosity on the electronic applications of polymer nanocomposites (specifically, photovoltaic cells), are briefly stated in subsequent sections.

2.1 Photovoltaic Applications

Photovoltaic cells are concerned with the conversion of light energy (primarily, sunlight) into electrical energy. The solar cells responsible for the conversion are made of semiconductors. The optical material, which absorbs the light, is arranged in layers and modules to form a complete system of light energy transformation into electrical energy [19]. Since 1954 when inorganic solar cell was developed, the most popular material for the fabrication of photovoltaic is silicon [20]. Coupled with other disadvantages, silicon being a hard material, is very expensive, and its cost is directly proportional to the photovoltaic solar cells cost. Goetzberger and Hebling [21], highlighted some requirements for an ideal solar cell material. The requirements, include: low bandgap, non-toxicity, facile production techniques, high photovoltaic conversion efficiency, durability, sustainability, and readily available materials. Basically, polymer nanocomposite for photovoltaic application, is promising owing to its reduced fabrication cost, availability of materials, and

high conversion efficiency [22]. Crystalline silicon, amorphous silicon, cadmium telluride, copper indium di-selenide, quantum dot, perovskite, and polymer-based materials are some of the commercial and industrial production materials that are suitable for solar cells manufacturing.

The conjugated polymer, poly(1-methoxy-4-(2-ethylhexyloxy)-*p*-phenylenevinylene), was composited with zinc-oxide nanorods to produce an active layer for a photovoltaic solar cell [23]. The fabrication process followed the addition of 40 ml of zinc-oxide nanorods to the as-prepared poly(1-methoxy-4-(2-ethylhexyloxy)-*p*-phenylenevinylene), and magnetically stirred for 24 h under nitrogen atmosphere. The precipitate obtained through the centrifugation process was vacuumized at room temperature for several days. From the experimental results, the nanocomposite active layer enhanced the performances of the photovoltaic device with a short circuit current density of 0.19 mA/cm², open circuit of 0.59 V, and power efficiency of 0.3%. The fabrication of the solar cell involved the following procedures:

1. Preparation of the indium-tin-oxide substrate.
2. Spin coating of poly(3,4-ethylenedioxythiophene)/polystyrene sulfonate on the substrate.
3. At room temperature, the deposition of the polymer nanocomposite via the spin coating technique was performed on the poly(3,4-ethylenedioxythiophene)/polystyrene sulfonate.
4. The prepared device in stage 3 was vacuumized for 24 h to remove the residual solvent and to ensure the uniformity of the layers.
5. On the active layer (i.e., the polymer nanocomposite), was lithium fluoride evaporated, followed by the deposition of aluminum at controlled rate and pressure.
6. The solar cells were transferred to a nitrogen glove-box environment, where the sealing of the solar cells takes place.

An active layer of a typical photovoltaic device is the absorber layer, which is responsible for absorbing quantum of electromagnetic field (photon) from sunlight. From the absorber layer, electron–hole pairs are generated to initiate photovoltaic effect. Ntanovasilis et al. [24], proposed a bulk heterojunction active layer for the manufacturing of photovoltaic cells. The bulk heterojunction active layer was composed of poly(3-hexylthiophene-2,5-diyl)/[6,6]-phenyl-C61-butyric-acid-methyl-ester and poly(2,7-carbazole-alt-4,7-dithienyl-2,1,3-benzothiadiazole)/[6,6]-phenyl-C71-butyric-acid-methyl-ester composites. Poly(3-hexylthiophene-2,5-diyl) is a conducting polymer with excellent properties. The polymer, with its excellent charge carrier mobility, and the semi-conducting properties of the polymer, make it suitable for various electronic applications. On the other hand,

[6,6]-phenyl-C61-butyric-acid-methyl-ester and [6,6]-phenyl-C71-butyric-acid-methyl-ester, are electron acceptors, derived from fullerene. The fullerene cage of C71 is characterized with high electron transportability than its fullerene cage counterpart of C60 [25]. From the results of Ntanovasilis et al. study, the photovoltaic cells fabricated with the active layer poly(2,7-carbazole-alt-4,7-dithienyl-2,1,3-benzothiadiazole)/[6,6]-phenyl-C71-butyric-acid-methyl-ester composites, exhibited better photovoltaic performances than the other bulk heterojunction active layer. The photovoltaic cell used indium-tin-oxide as the substrate and poly(3,4-ethylenedioxythiophene)/polystyrene sulfonate as the passive layer. The effect of porosity was indirectly investigated by Ntanovasilis et al. by using different deposition methods for the passive and active layers. The spin-coating of the passive layer and the injection- printing of the active layer produced solar cells with better power conversion efficiency than the inkjet-printing of both the passive and active layers.

The enhancement of photovoltaic devices properties, via the hybrid of organic and inorganic semiconductors, has shown promising benefits. The bulk heterojunction active layers benefit from the high aspect ratio of the interface and the facile processing methods of the polymeric materials. Owing to the photoluminescent and solubility properties of poly(2-methoxy-5-(2-ethylhexyl-oxy)-*p*-phenylenevinylene)—(MEH-PPV), and the electrical, optical, and physical properties of silicon-nanowires, the hybrid of the polymer and the inorganic silicon-nanowires production, was carried out by Maaref et al. [26], for photovoltaic application. The fabricated photovoltaic cell contained indium-tin-oxide as the substrate, MEH-PPV/silicon-nanowires as the active layer, and aluminum as the contact. The solar cell produced a current density of $\sim 0.39 \frac{\mu\text{A}}{\text{cm}^2}$.

A bulk heterojunction active layer consisting of the nanocomposite of poly(phenylene-vinylene), poly(vinyl alcohol), and zinc-oxide was prepared for solar cell application by Wang et al. [27]. To fabricate the poly(phenylene-vinylene)/poly(vinyl alcohol)/zinc-oxide nanocomposite, Wang et al. added 0.1 M aqueous solution of zinc acetate to the hybrid of poly(phenylene-vinylene)/poly(vinyl alcohol) composite, and magnetically stirred the copolymer at 70 °C. The cast deposition of the zinc-polymer based heterojunction active layer, was performed on indium-tin-oxide, already laid with poly(3,4-ethylenedioxythiophene) as the passive layer, and oven-dried at 70 °C for 2 h. The solar cell produced was thereafter, vacuumized at 160 °C for 6 h. The results obtained, showed that the active layer possessed a high interface area—the high interface area in the nanocomposite, is essential to reduce voids and enhance the charge carrier mobility in the photoactive layer nanocomposite system [28].

Generally, trying to prevent particles agglomeration in nanocomposites for photovoltaic applications has often led

to the compromise of the charge carrier mobility of the nanocomposite. In other words, the application of surfactants or dispersants to ameliorate the agglomeration of nanoparticles in polymer nanocomposites, is detrimental to the charge carrier mobility and the exciton dissociation [29]. Photovoltaic cells efficiency is directly related to the effective exciton dissociation and the charge carrier mobility of the active layer. Therefore, appropriate nanoparticles and polymer mixing strategies must be explored to optimize the nanoparticles' dispersion and to concurrently enhance the charge transport and the exciton dissociation of the nanocomposites for the maximum efficiency of photovoltaic devices. Since the active layer is a semiconductor, the bandgap and the optical absorption properties of the material must be adequately controlled.

The active layer made of poly(vinyl alcohol)/cuprous-iodide nanocomposite, fabricated by El-Mansy et al. [30], produced a low power conversion efficiency. However, El-Mansy et al. reported that the power conversion efficiency can be improved by the addition of fullerene derivatives. Therefore, poly(vinyl alcohol)/cuprous-iodide nanocomposite was facilely prepared by dispersing copper-dichloride into the magnetically-stirred poly(vinyl alcohol), followed by the drop-wise addition of sodium-iodide. The poly(vinyl alcohol)/cuprous-iodide nanocomposite obtained was spin-coated on the topmost layer of the passive material (poly(3,4-ethylenedioxythiophene)), and thereafter, a 90 nm thickness of aluminum was deposited on the active layer. El-Mansy et al. concluded that the hole carrier mobility of the active layer increased as the cuprous-iodide concentration increased in the polymer matrix.

During the fabrication of a bulk heterojunction active layer, consisting of poly(3-hexylthiophene) and nitrogen-doped-carbon-nanotubes, Keru et al. [31], investigated the effects of two synthesis techniques on the photovoltaic properties of the nanocomposite. They observed that an in-situ polymerization of the nanocomposite, showed excellent photovoltaic properties than the same product, obtained via the solution mixing method. In the case of the in-situ polymerization route, the polymer monomers are usually polymerized directly, on the surface of the nanofillers, while the direct solution mixing technique, involves the mixing of the polymer and the nanofiller as different entities. As shown in Fig. 1a, the Raman vibration peaks of the nanocomposites prepared by the in-situ polymerization and direct solution mixing techniques, showed the effects of synthesis techniques on the effective properties of nanocomposites. As can be seen in the figure (Fig. 1a), the nanocomposite prepared by the direct solution mixing route depicts a poor interfacial-interaction, as evident by the repetitive peaks of the poly(3-hexylthiophene). However, the nanocomposite showed better interfacial interaction when prepared via the in-situ polymerization technique. Moreover, the dispersion

of the nanofiller is further displayed by the scanning electron microscopy image (Fig. 1b, c). Agglomeration and voids can be observed in the nanocomposite prepared by the direct solution mixing technique. The void and agglomeration effects are inimical to the exciton dissociation, charge carrier mobility, thermal stability, and mechanical properties of the fabricated photovoltaic cell active layer. The current–density/voltage characteristics and the complete schematic of the poly(3-hexylthiophene)/nitrogen-doped-carbon-nanotubes solar cell arrangements of the constituents of the nanocomposite, is shown in Fig. 1d, e.

The generation of electron–hole pairs in solar cells, significantly depends on the photovoltaic active materials. The absorption of photon by the solar cells is a function of the semiconductor energy bandgap [32]. That is, an active material with low energy bandgaps will require low energy to absorb photons for the generation of electron–hole pairs. From the elementary photon energy equation presented in Eq. 1, it is obvious that the long-wavelength of light will decrease the generation of electron–hole pairs due to the reduced photon energy. However, when the energy bandgap of the active material in a semiconductor device is relatively small, it implies that the energy required for electron excitation from the valence band to the conduction band, is comparatively low [33]. In such cases, even the photons with lower energy state, associated with longer wavelengths, will effectively initiate electron transitions across the bandgap, leading to the creation of electron–hole pairs within the material.

$$E_p = \frac{hc}{\lambda}, \quad (1)$$

where h , c , and λ are the Planck's constant, speed of light, and the photon wavelength. The benefits of an active layer small-energy bandgap include:

1. Increase in short circuit density [34].
2. Often, the bulk heterojunction active layer of organic photovoltaic cells, is made of donor and acceptor materials. This design is expected to dissociate the excitons through the energy difference between the highest occupied molecular orbit (HOMO) and the lowest unoccupied orbit (LUMO). Consequently, the open-circuit voltage largely depends on the energy offset between the HOMO and the LUMO. A photoactive layer with narrower bandgap, causes a reduction in the open-circuit voltage, and invariably, minimizes the charge transfer loss due to the reduction in the energy difference between the donor and the acceptor materials [35].

In fact, the performances of photovoltaic photoactive layer can be controlled by the synthesis techniques

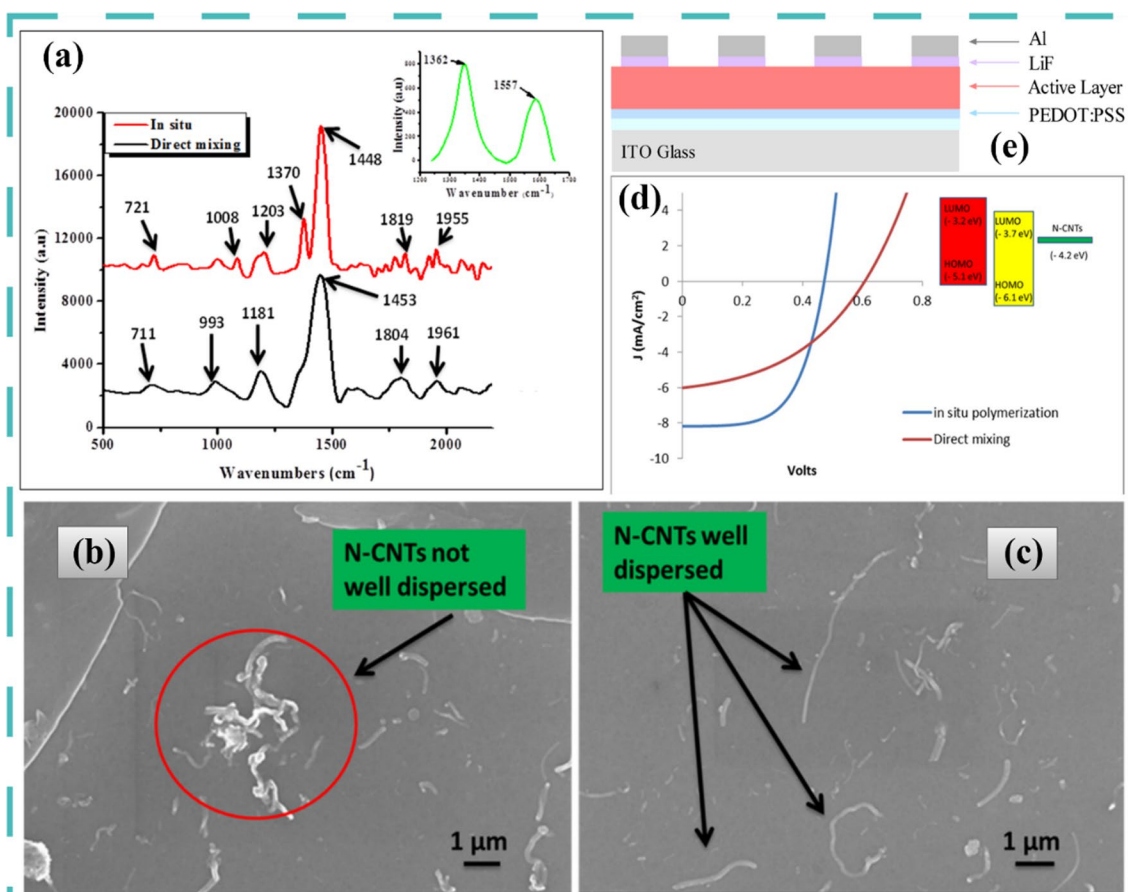


Fig. 1 Poly(3-hexylthiophene)/nitrogen-doped-carbon-nanotubes nanocomposites: **a** Raman spectroscopy results, **b** scanning electron microscopy (SEM) image showing agglomeration and voids, **c** SEM

image showing a well dispersed nanofiller, **d** current density–voltage curves and **e** solar cell (Reproduced with permission from ref. [31]. Copyright 2015, MDPI)

employed and other factors, such as: bandgap, conductivity, energy levels of HOMO and LUMO, and morphology. A ternary polymer nanocomposite consisting of poly(ortho-phenylene-diamine-*o*PD), poly(meta-phenylene-diamine-*m*PD), and polypyrrole (PPy), was prepared by Abdel-Aziz et al. [36]. The bandgap and the optical characteristics of the hybrid polymers were controlled by using zero-pH hydrochloric acid. As shown in Fig. 2a, the oxidation of the polymerized monomers, was carried out by using ferric-chloride diluted with sodium-dodecyl-sulphate surfactant. The facily prepared ternary polymer composite was fabricated into a thin-film active layer by using the physical vapour deposition technique (Fig. 2b). The bulk heterojunction photoactive layer (Au/ternary polymer composite/silicon-wafer/aluminum) exhibited a 9.26% at 150 mW/cm² power conversion efficiency. As reported by Abdel-Aziz et al. without an external connected load, the active layer could deliver a current density of 3.96×10^{-3} A/cm² at an open-circuit voltage of 78.3×10^{-2} V (see Fig. 2c). It is important to note that the mobility of the charge carriers towards the electrodes

depends on the bandgap of the active layer and the electrical conductivity of the material—this phenomenological behavior relies largely on the production technique. The higher the voids in the composite, the higher the energy required to overcome the potential barriers. In addition, the direct and indirect bandgaps of the hybrid polymer composite, is ~ 2 eV (see Fig. 2d).

In another study [37], it was demonstrated that the incorporation of graphene-oxide in polypyrrole/copper nanocomposite, reduced the bandgap of the nanocomposite from 3.46 to 2.25 eV. The hybrid of the nanoparticles with the polymer was achieved by the ultrasonic dispersion of the mixture of polypyrrole and copper, followed by the chosen percentage inclusion of graphene-oxide. The polypyrrole/copper/graphene-oxide nanocomposite was thereafter electrochemically deposited on fluorine-doped tin-oxide. Nickel nanoparticles loaded-strontium titanate (SrTiO₃) was hybridized with poly(3-octyl-thiophene) to produce a bulk heterojunction active layer for solar cells [38]. It was observed by Adimule et al. that the choice of solvent and filler concentrations are influential factors, which contributed to the solar

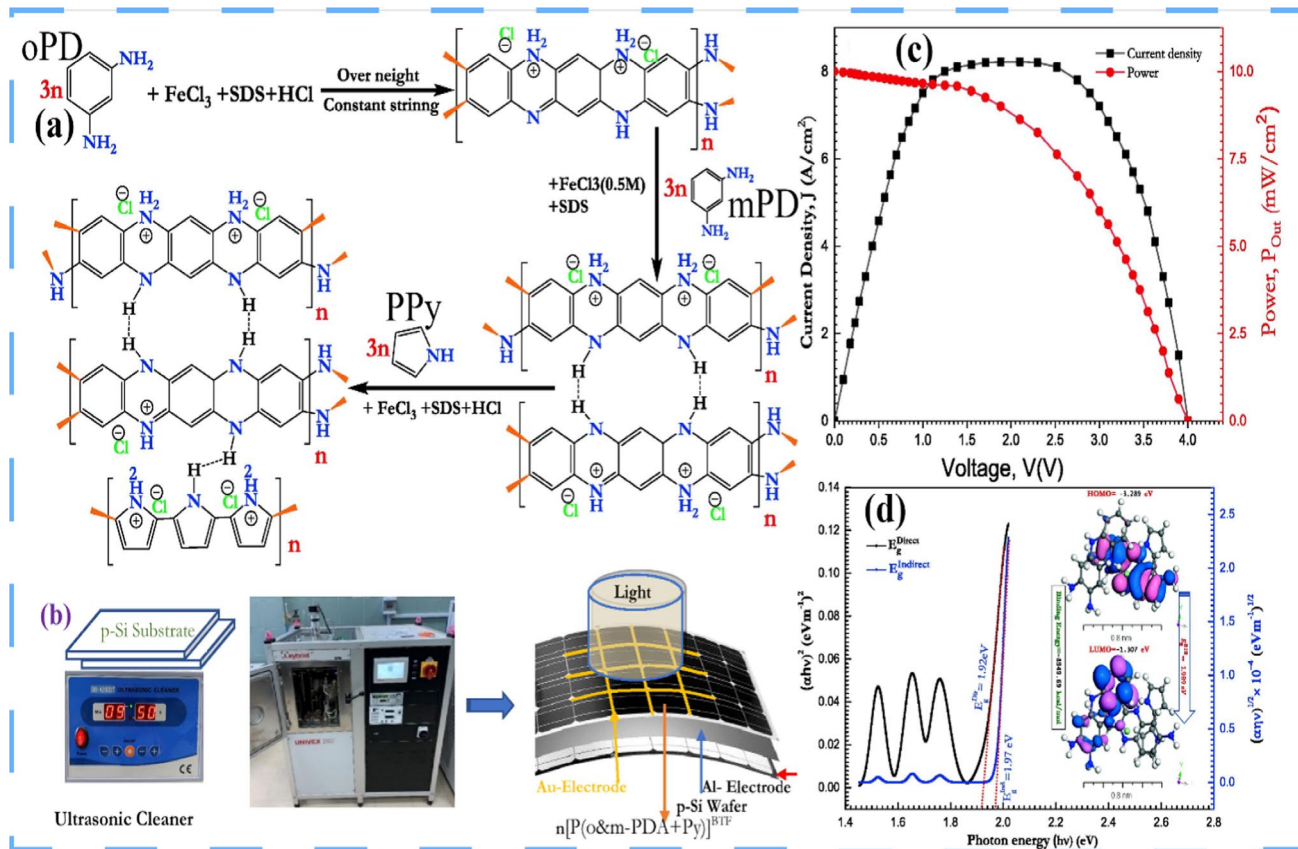


Fig. 2 Schematics representation of oPD/mPD/PPy bulk heterojunction photoactive layer: **a** preparation technique, **b** solar cell fabrication route, **c** current–density measurements and **d** direct and indirect

bandgap calculations (Reproduced with permission from ref. [36]. Copyright 2023, Elsevier Ltd)

cell active layer efficiency. The conventional parameters for optimizing and controlling the molecular and morphological features of bulk heterojunction active layer, include:

1. Solvent type.
2. Donor and acceptor concentrations.
3. Film thickness.
4. Pre- and post-treatment processes.

2.1.1 Defects or Voids Effects on Polymer Nanocomposite Photovoltaic Cells

As previously stated, defects/voids or induced porosity effects on polymer nanocomposite photovoltaic cells can reduce the overall photovoltaic performances of the solar cells. One contributing factor to this effect is the synthesis technique, choice of compositing materials, and the chosen synthesis parameters [39]. The enhancement in conjugated polymer photovoltaic properties has been tremendously achieved by incorporating metal, metal-oxide, and carbonaceous materials into polymer matrices. The advantages [40] of the bulk heterojunction active layer may include:

1. Simple synthesis techniques.
2. Enhanced charge extraction from the active layer. This effect is essential for improving photovoltaic photocurrent and power conversion efficiency.
3. Reduction in the energy bandgap between the semiconductor energy level and the electrode work-function.
4. Reduces exciton-recombination at the interfaces.

However, because of the defects in the active layer of solar cells, the photovoltaic cells' performances can be hampered by the trap state. As reported by Wang et al. [41], an excessive inclusion of lead (II)-iodide in perovskite devices for photovoltaic applications can expand the trap state density, increase the trap state distribution, enlarge the exciton-binding energy, hinder the separation of photo-induced exciton, and invariably, reduce the effective performances of the photovoltaic cells. In a nutshell, an excessive or high concentration of nanoparticles in organic semiconductors can deter the charge transfer process and eventually, decrease the overall performance of the intended fabricated solar cells due to the trap state. The power conversion efficiency of photovoltaic cells can be quantified by the proportion of

trap-assisted recombination, usually caused by localized deep trap-states [42]. The high concentration of nickel-oxide nanoparticles in poly(3-hexylthiophene), has also been reported to induce deep trap state in the photoactive layer of the organic solar cells [43].

Furthermore, polymer nanocomposite photovoltaic cells' problems [44, 45] can be summarized into followings:

1. Poor mobility of charge carrier.
2. Recombination of photo-generated charge carrier.
3. Instability of active layer at the interface between the charge transport layer and the electrodes, when exposed to heat, radiation, and moisture.
4. Phase separation challenges when there is donor and acceptor miscibility/solubility problems.

There is a plethora of factors which may contribute to the problems of polymer nanocomposites photovoltaic cells. For instance, the electrical conductivity and charge mobility rate of silicon can be thoroughly enhanced via impurities inclusion. However, for polymer nanocomposites, uncontrolled impurities inclusion at the bulk state, can drastically demean the intended photoelectric properties of the nanocomposites [45]. In order to reduce the recombination of the photo-generated charge carriers in polymer nanocomposites, Wilken et al. [46], suggested that, solar cells active layers, made of polymer nanocomposites, must be carefully prepared and highly crystalline with phase purity. Recombination of the photo-generated charge carriers is one of the leading factors that contribute to a low overall power conversion efficiency of solar cells. This effect often leads to energy loss as heat before the electrons and holes reach the external connected circuit.

The homogeneous dispersion of additives in the polymer matrix and the smooth morphology of the fabricated thin-film nanocomposite active layers, can ameliorate the trap state. Trap state causes the recombination of the photo-generated charge carriers and the reduction of photovoltaic cell power conversion efficiency. In order to mitigate the photothermal instability problem of polymer nanocomposite active layer, Paci et al. [47], proposed the composition of poly(3-hexylthiophene) and ([6,6]-phenyl-C6-butyric acid methyl-ester) copolymer with surfactant free gold nanoparticles. The 5% gold nanoparticles inclusion in the matrix of the copolymers, enhanced the bulk heterojunction active layer stabilities and reduced the recombination of the photo-generated charge carrier.

The bulk heterojunction polymer nanocomposites active layers for solar cells fabrication, require an optimized blending. The nanocomposites must be free from defects: the donor and the acceptor domains must be well packed to have an efficient exciton dissociation and improve the electrons/hole transportation.

Phase segregation is another defect that can occur in polymer nanocomposite bulk heterojunction active layers. For instance, Ebadian et al. [48], reported that the electron mobility of poly(3-hexylthiophene)/([6,6]-phenyl-C6-butyric acid methyl-ester) composite, decreased as the annealing time increased. The effect was attributed to the phase segregation of poly(3-hexylthiophene) from ([6,6]-phenyl-C6-butyric acid methyl-ester) as the annealing time increased. Moreover, the reduction in the electron mobility due to phase segregation, resulted in the degradation of the photo-activity of the solar device and its durability. In the work of Ozcan et al. the hybridization of poly(3,4-ethylenedioxythiophene)/poly(styrene-sulfonate) and graphene-oxide nanoparticles for hole transport layer in an inverted hetero-junction solar cell active layer, was presented [49]. From the structural analysis of the nanocomposite, a phase segregation was found to occur between the graphene-oxide and poly(3,4-ethylenedioxythiophene), while it interacted with polystyrene-sulfonate. The interaction between graphene-oxide and poly(3,4-ethylenedioxythiophene) may increase the electrical conductivity of the nanocomposite due to the removal of the polystyrene-sulfonate insulating part. Nevertheless, the power conversion efficiency of the graphene-oxide/poly(3,4-ethylenedioxythiophene)/polystyrene-sulfonate) nanocomposite active layer was very low. This may be because of the defect caused by the phase segregation.

In summary of this section, the performances of the final fabricated polymer nanocomposite active layer for photovoltaic device, are functions of:

1. The composite materials
2. The composite synthesis techniques
3. The composite synthesis parameters.

The processing conditions, such as: blending solvent, additives, deposition treatment, and thermal annealing, are important control parameters for the modification of the morphology of bulk heterojunction active layers [50]. Pivrikas et al. [51], suggested the use of slow-drying solvents, chemical additives, and self-assembling post-production process for bulk heterojunction solar cells active layers. The suggested techniques were envisaged to control adequately the materials morphology for high-performance photoactivities. Regardless of whether the solar cells active layer is single, bilayer, or bulk heterojunction components, an un-optimized fabrication process, will result in a poor exciton dissociation, high-recombination loss, and low-photon harvesting photovoltaic cells performances.

Defects and unwanted porosities in the photoactive layers, made of polymer nanocomposites, can be controlled by the selective modification of the organic semiconductor molecular structures. An optimized control of the photoactive

materials' morphology will involve careful dispersion of additives in the polymer matrices to ensure perfect interfacial interaction between the constituent materials. Even though, the development of non-fullerene acceptors for bulk heterojunction active layers was to abate fullerenes tendency to aggregate, and to reduce their morphology instability [52]. However, the optimization process parameters and the careful hybridization of the materials are crucial for achieving an efficient charge transportation and minimization of the losses due to recombination in organic photovoltaic cells.

In the work of Zhang et al. graded-bulk heterojunction active layer was prepared by using solvent-sequential deposition technique [53]. The proposed solvent-sequential deposition was aimed to ameliorate phase separation challenges. Zhang et al. further ascertained the fact that the bulk heterojunction active layer, fabricated by solvent-sequential deposition, can reduce the excessive aggregation induced by the conventional preparation methods. As shown in Fig. 3, the donor (poly[(2,6-(4,8-bis(5-(2-ethylhexyl)-3-fluoro)thiophen-2-yl)-benzo[1,2b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'c']dithiophene-4,8-dione)], often represented as: PM6) and the acceptor (BTP-eC9, a non-fullerene acceptor), were sequentially deposited on the indium-tin-oxide/poly(3,4-ethylenedioxythiophene)/poly(styrene-sulfonate) substrate (see Fig. 3a, b). The sequential deposition of the donor and acceptor materials was shown to have large thickness advantage. However, as the thickness of the active layer kept increasing,

the open-circuit voltage and power conversion efficiency kept reducing, while the current-density kept increasing (see Fig. 3c). In addition, the method was able to produce a balanced donor and acceptor interlayer with almost equal charge mobility (Fig. 3d). The conventional bulk heterojunction active layer, showed high disparity between the electron and hole mobility. The overall power conversion efficiency of the solar cell ranged between ~17.48 and ~17.54%.

Furthermore, the correlation between porosity and polymer nanocomposite photovoltaic cell performances is not linear. For instance, the photovoltaic activity of porous-metal-oxide/polymer nanocomposites can be limited due to the infiltration of polymer into the pores of the metal-oxide constituent [54]. The infiltration of polymers that have bulky chains into the porous nanoparticles, may result in incomplete coverage; hence, gaps or voids are created, which would potentially deteriorate the light absorption efficiency and the generation of charge carriers. To ameliorate this effect, the surface of the porous nanofillers must be modified, while the molecular structure and the bulky polymer chains are optimized. Moreover, the concentration of the nanofiller, in the polymer matrix, is expected to be relatively small for it to be able to protect the mechanical and photoactive properties of the solar cell active layer. Defects due to the production processes can be reduced by the adequate control of the volume concentration of the fillers in the polymer matrix. In addition, interface defects can be corrected by using suitable synthesis techniques.

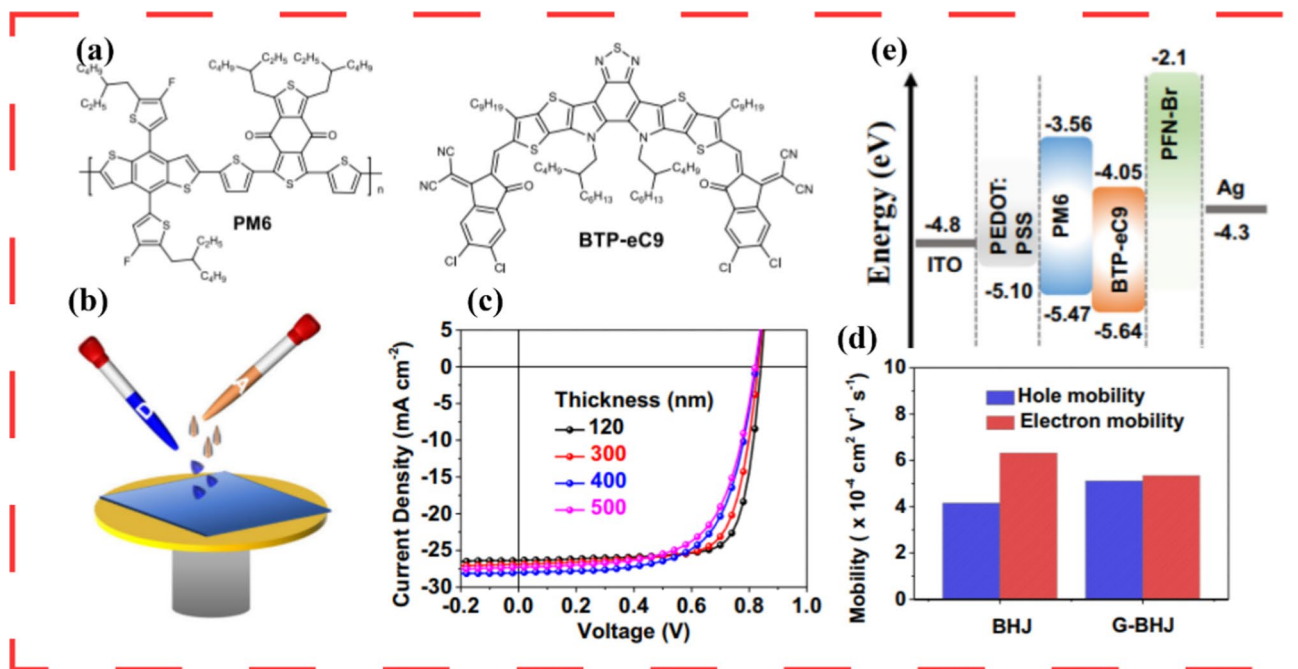


Fig. 3 Graphical representation of the PM6-BTP-eC9 donor/acceptor scenario: **a** chemical structure, **b** sequential deposition technique, **c** current–density/voltage characteristics, **d** electron/hole mobility and

e typical photovoltaic device (Reproduced with permission from ref. [53]. Copyright 2021, Nature Communications)

3 Polymer Nanocomposites for Biomedical Applications

Polymer nanocomposites for biomedical applications in human bodies, have the benefits of environmental friendliness, biocompatibility, and biodegradability. Various polymer nanocomposites have been developed for the cure of cancers, bacterial pathogens, while some are for drug deliveries, tissue engineering, and biomedical sensors [55–57]. The commonly used polymers for biomedical applications, cut across both natural and synthetic polymers. Examples of natural polymers include chitin or chitosan, starch, alginate, soy, collagen, and fibrin gels. The synthetic polymers counterparts, include: PCL—poly(ϵ -caprolactone), PGA—poly(glycolic acid), PLA—poly(lactic acid), PHB—poly(hydroxyl butyrate), PLGA—poly(lactic-co-glycolic acid), PEG—polyethylene-glycol, PVA—polyvinyl-alcohol, PU—polyurethane, PMMA—poly(methyl-methacrylate), PET—poly(ethylene-terephthalate), PCLA—poly(ϵ -caprolactone-*co*-lactide), and PDO—polydioxanone [58]. Some conducting polymers, include: polypyrrole (PPy), polyaniline (PANI), and polyvinyl-pyrrolidone (PVP) [59]. The commonly used fillers, are briefly summarized in Table 1.

For sensor applications, bio-nanocomposites must meet the electrical conductivity requirements capable of performing biosensing and bioelectronic activities. In like manner, the nanocomposites must be mechanically viable for applications, such as: skin scaffolding, and bone tissue engineering. Generally, bio-nanocomposites for biomedical applications, must respond to pH and temperature of measurands at high sensitivity. They must be biocompatible, stable, and cheap. During the fabrication of the polymer nanocomposite for biomedical applications, the properties of the biodegradable/compatible polymers, such as: flexibility, and non-toxicity, are expected to be retained, while improving the mechanical strength and bioactivity

of the polymers. The nanoparticle inclusion has the benefit of large surface area, mechanical stability, solubility, and conductivity [61]. Bio-nanocomposite devices may be revolutionizing due to their lightweight, simple processing techniques, flexibility, and low cost. However, poor interfacial interaction between the constituent materials, is not desirable for their expected performances [62]. As summarized by Kumar et al. [63], the processing techniques of polymers may be easy; nevertheless, bio-nanocomposite devices have complex fabrication methods. Coagulation or aggregation due to weak interaction between nanofiller and polymer matrix, will reduce the bioactive properties of the nanocomposites. Toxicity release from free-nanocomposites can also hamper the unique properties of bio-nanocomposites. In addition, the use of surfactants for nanofiller dispersibility can be very harmful to the expected bio-properties of bio-nanocomposites. Therefore, a careful selection of the fabrication techniques and desired definition of the needed parameters, such as: surface charge, surface chemistry, crystallization, and dispersion stability of nanofillers, must be carefully considered, while preparing polymer nanocomposites for biomedical applications. The following sections screened the different bio-nanocomposite devices, preparatory techniques and how defects can alter the overall properties of the devices.

3.1 Bio-nanocomposites for Tissue Engineering

Tissue engineering has been an integral part of biomedical procedures for purposes of: repairing, restoring, replacing, maintaining, and improving tissue functions [64]. As shown in Fig. 4, polymer nanocomposites for tissue engineering applications, cut across, viz: scaffolds, cells, and biological means, to repair and restore damaged body tissues [65]. For example, scaffolds are three-dimensional structures used to facilitate, support, and guide the production of cells and tissues in the body. Majorly, tissue engineering is concerned with the rejuvenation of damaged tissues and organs through

Table 1 Polymer nanocomposite natural and synthetic fillers for biomedical applications [60]

Category	Synthetic fillers	Natural fillers
Ceramic fillers	Silicon carbide (SiC), aluminum oxide (Al_2O_3), zinc oxide (ZnO), boron carbide (B4C), titanium dioxide (TiO_2), zirconium dioxide (ZrO_2), tungsten carbide (WC)	Hydroxyapatite, tricalcium phosphate, and calcium phosphate
Metals and metal-oxides	Titanium dioxide (TiO_2), zinc oxide (ZnO), iron oxide (Fe_3O_4), silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), copper nanoparticles (CuNPs)	
Carbon-based fillers	Graphene, carbon-nanotubes, carbon-nanofibres	Graphite
Mineral fillers	Calcium carbonate ($CaCO_3$), magnesium hydroxide ($Mg(OH)_2$), and zeolite	
Others		Cellulose, jute, sisal, hemp, bamboo fibers, grass fibers, bagasse, and chitin nanofibers

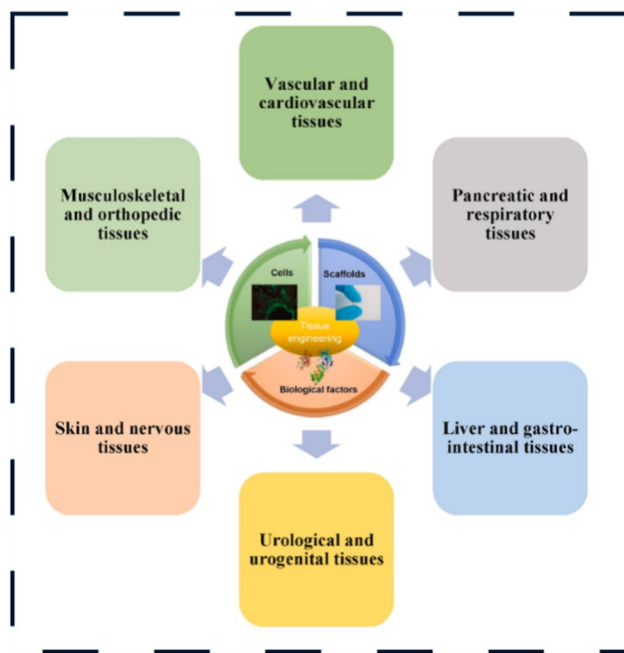


Fig. 4 Tissue engineering applications for tissue repairs (Reproduced with permission from ref. [65]. Copyright 2023, Elsevier Ltd)

the design and fabrication of biomimetic scaffolds, the incorporation of cells and growth factors, and the creation of functional tissue constructs that can integrate with the host's biological systems to promote regeneration and the repair of tissues [66]. Polymer nanocomposites, consisting of biodegradable/compatible polymers and ceramic or metallic nanoparticles, have been utilized for the manufacturing of scaffolds. Pore size, porosity, mechanical, and bioactivity properties of the fabricated biomimetic scaffolds, are significant to cells/tissues proliferation, bone ingrowth, osseointegration of bone implant, and biomechanical requirements of the biomimetic scaffolds.

The essence of nanofillers or nanoparticles in biodegradable polymers is for the enhancement of the overall nanocomposite's mechanical properties and also to improve the stimulation of cellular-adherence due to the nanoparticles large surface areas [67]. Besides the mechanical properties, the bio-nanocomposites made of polymers and nanofiber materials can withstand corrosion and fatigue at high resistance. The overall properties of scaffolds, made of bio-nanocomposite, should include: high porosity with appropriate pore size, biocompatibility, biodegradability, and adequate degradation rate [68]. Polymer nanocomposite for scaffolds, have been produced by employing the following techniques [69]:

1. Sacrificial template
2. Solvent casting
3. Leaching

4. Foaming
5. Gas foaming
6. Freeze drying.
7. Phase separation
8. Electrospinning
9. Emulsification
10. Sintering
11. 3D-printing (inkjet, laser-assisted, micro-valve, micro-extrusion, stereolithography, fused deposition modeling, and selective laser sintering).

Porosity and technical defects (such as surface irregularities, roughness, or microstructural features) are valuable factors to the bioactivities of bio-nanocomposites, i.e., porous scaffolds have been demonstrated as effective enhancers for bone ingrowth. Porous scaffolds encourage cellular growth for tissue rejuvenation. However, there is a threshold of porosity for an optimum performance of the biomimetic devices. It is, however, critical to bear in mind that above the threshold, porosity will lead to the trade-off of the mechanical strength of the scaffold. Therefore, during the design of scaffold for biomimetic application, the extent to which porosity must impact the compressive and tensile strength of the scaffold should first be determined. The processing conditions, and the nature of the compositing materials are essential factors, which can be used to determine the required limit of the bio-nanocomposite device porosity [70]. The rate of degradation of biomimetic scaffolds is also related to how porous the polymer nanocomposites are. Karageorgiou and Kaplan reported that when the needed properties of scaffolds involve high porosity, then the scaffold should be designed with materials that have low degradation rate. Conversely, scaffolds fabricated with high degradable materials must be designed to possess low porosity. In both cases, the mechanical properties of the nanocomposites are preserved, and the regeneration of new tissues can be improved.

By using solvent casting synthesis technique, Jiang et al. prepared PVA/sodium-alginate/calcium-ions/titanium-dioxide nanocomposite for bioactive scaffold [71]. The blend of sodium alginate biopolymer with PVA was to reduce the swelling characteristics, low mechanical strength, poor thermal stability, and the hydrophobicity associated with sodium alginate. To enhance the new tissue regeneration property of the nanocomposite, a titanium dioxide-doped calcium ion, was expected to contribute to the growth of the new bone formation due to the release of calcium ion. Moreover, the intermolecular interactions, porosity, and stability of the bioactive scaffold for new cell proliferation was enhanced by the addition of the biocompatible PVA. Figure 5 shows the porosity, formation characteristics, and biodegradability of the bio-nanocomposite scaffold. The homogenous dispersion of the filler (titanium dioxide-doped calcium ion) in

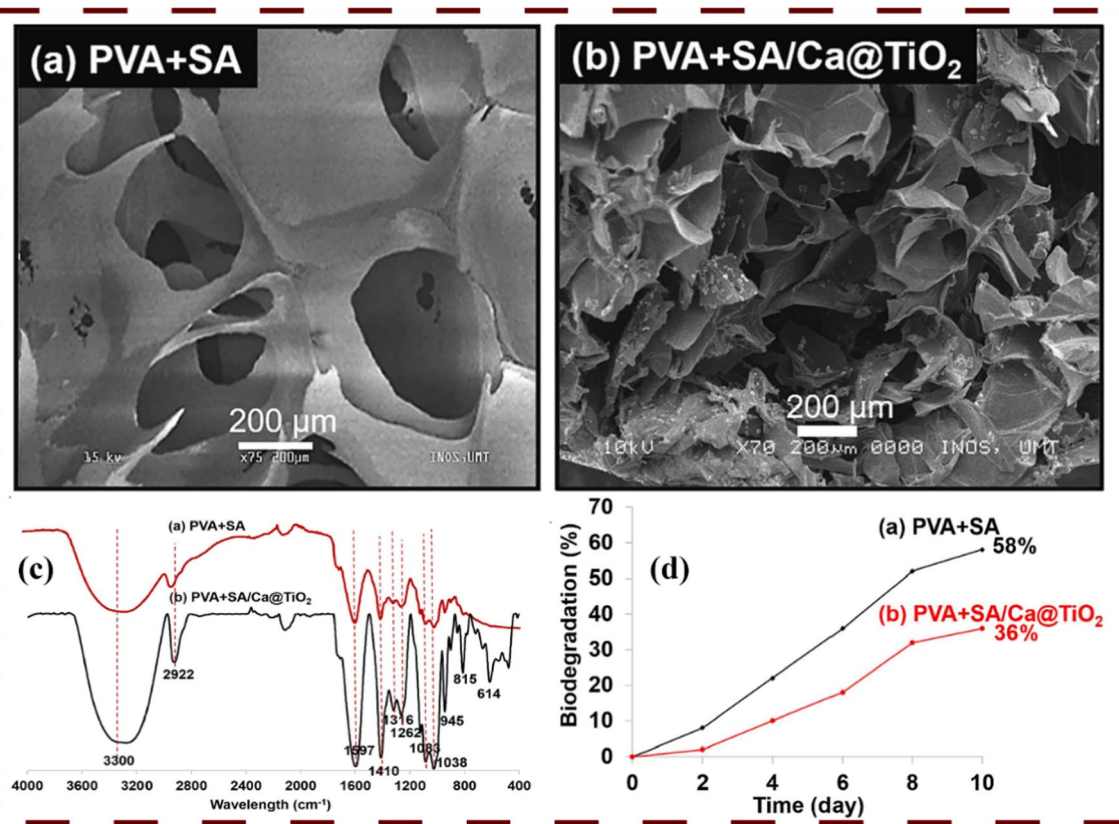


Fig. 5 SEM micrographs of PVA/sodium alginate/titanium-oxide doped calcium ion nanocomposite scaffold **a, b** porosity, **c** formation characteristics and **d** biodegradability rate (Reproduced with permission from ref. [71]. Copyright 2023, Elsevier Ltd)

the hybrid-biopolymers promoted porosity in the bioactive scaffold (Fig. 5a, b). In addition, there existed an intermolecular interaction in the nanocomposite, and invariably, a low degradation rate (Fig. 5c, d).

The interaction of the compositing materials should be the main interest, while fabricating scaffolds for biomedical applications. A super-blended biodegradable/compatible polymer with suitable nanofillers will maintain excellent mechanical and porous properties. The optimization of the filler concentration will also improve the biomechanical and bioactivity of the polymer nanocomposites. For instance, in the experimental investigation conducted by Niveditha et al. a mixture of β -cyclodextrin and zinc sulfide nanoparticles was fabricated via the sonification technique [72]. A magnetically stirred mixture of polyvinyl alcohol and chitosan in acetic acid and double-distilled water was added to the β -cyclodextrin capped zinc sulfide nanoparticles. The blended materials were, thereafter, electro-spun to produce a scaffold nanofilm with 100 nm diameter. The homogenous mixture of the polymer with the nanoparticles promoted the mechanical, porosity, hydrophilicity, and biodegradability properties of the nanocomposite. The polymer-zinc sulfide-based nanocomposite displayed a potential antimicrobial activity against bacteria and fungi.

Polymer/graphene-based nanocomposites for tissue engineering have been reported as viable materials for vascular and small vascular tissue engineering applications. Graphene can be modified and functionalized to have antibacterial properties. The antibacterial properties, coupled with the excellent mechanical, photonic, and thermal properties of graphene, the polymer nanocomposites containing graphene, can facilitate the proliferation of vascular muscle cells. In addition, polymer graphene-based nanocomposite can act as pro-angiogenesis protein carrier with the tendency to promote tissue engineering for wound healing, and regenerative medicine [73]. Figure 6a, b provides a concise information on the applications of polymer graphene-based nanocomposites for biomedical applications. Graphene (in different states) has different nomenclatures [16], which include: reduced graphene oxide, graphene foam, graphene oxide, graphene, few-layered graphene, and exfoliated graphene (Fig. 6c). The antimicrobial mechanisms of graphene-based materials for scaffold (Fig. 6d), include nano-knives, wrapping, and oxidative stress [74]. The incorporation of graphene into scaffold materials can enhance the antimicrobial activity of the biomimetic scaffold due to the generation of reactive oxygen species (ROS), when graphene interacts with biological fluids. It is also very important to optimize

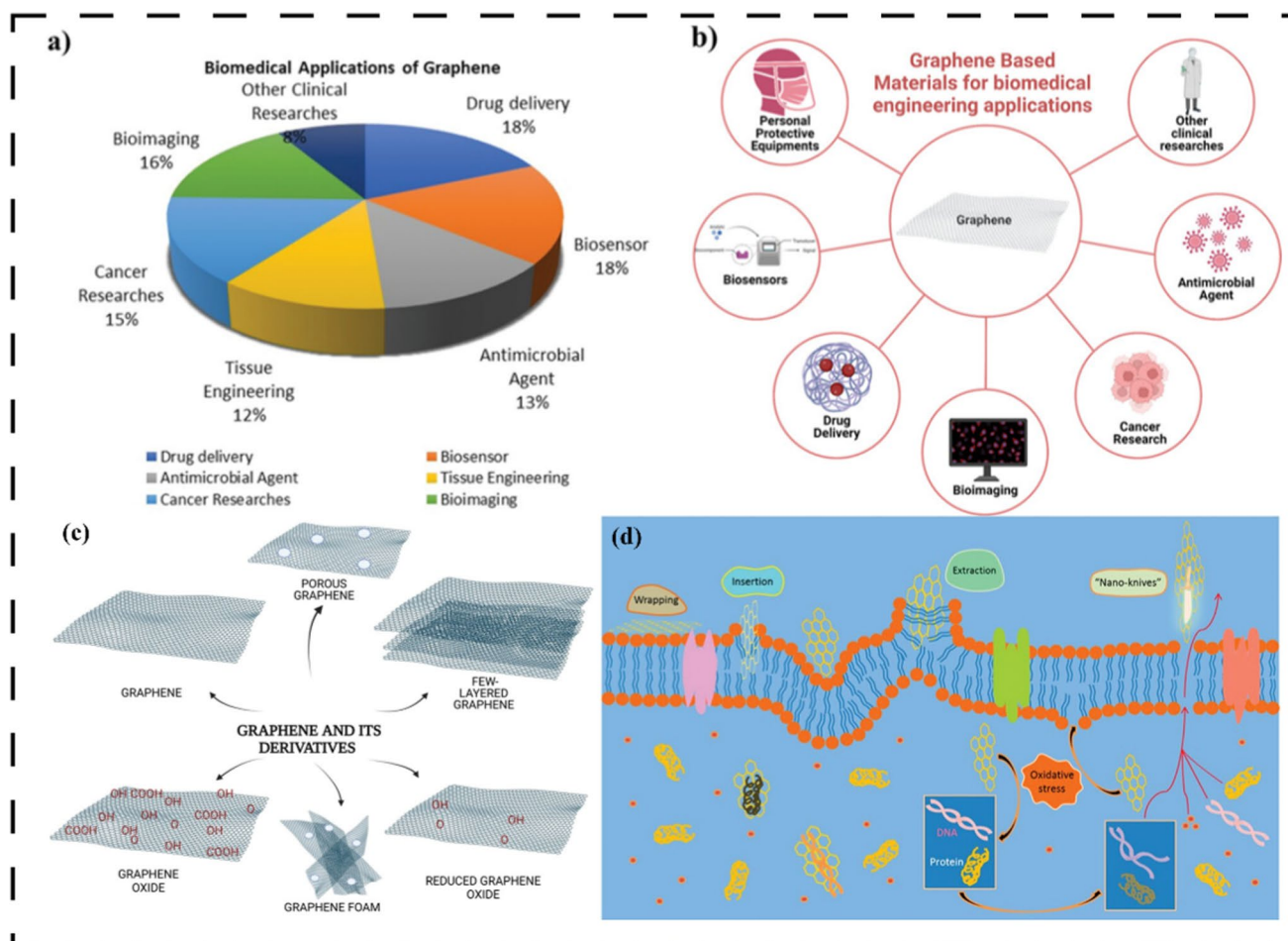


Fig. 6 Graphene-based nanocomposites: **a** biomedical applications distributions, **b** general biomedical applications, **c** graphene family and **d** antimicrobial bioactivity (Reproduced with permission from ref. [74]. Copyright, 2022. Wiley)

the concentration of graphene in polymer nanocomposite scaffold—excessive reactive oxygen species may hamper tissue proliferation [75].

Singh et al. studied the tissue engineering application of polymer nanocomposite scaffold by compositing polyurethane, graphene, and calcium hydroxyapatite (PUG-CHAp) [76]. In the investigation, graphene/hydroxyapatite and concentration optimizations were carried out. As shown in Fig. 7a, the solvent casting-leaching technique was engaged in the production of the polymer/graphene-based scaffold. The method was chosen to produce a smart-biomimetic scaffold with excellent mechanical, porous, and pore size properties. During the production process of the scaffold from the PUG-CHAp nanocomposite, the nanocomposite was dissolved in dimethyl-formamide and tetrahydrofuran and then, properly centrifuged. Prior to the centrifugation process, the PUG-CHAp nanocomposite was mixed with sodium chloride. The salted PUG-CHAp nanocomposite, in double distilled water was, thereafter, subjected to the evaporation process to

produce an optimized porous scaffold. Figure 7b shows the porous and the non-porous network of the PUG-CHAp nanocomposite. The cytotoxicity effect of graphene oxide, as displayed in Fig. 7c, shows that as the concentration of graphene oxide increases in the nanocomposite, the cell viability began to reduce—low graphene concentration is suggested to keep the scaffold nontoxic, while its mechanical and porous structure are maintained.

In an investigation conducted by Lee et al. a porous, waterborne-biodegradable polyurethane was composited with graphene nanoparticle for neurovascular regeneration [77]. To avoid the negative impact of process induced porosity on the mechanical property of the scaffold, Lee et al. facilely prepared the nanocomposite and air-dried it in Teflon plates (Fig. 8a). However, after rolling the nanocomposite film into conduits, the result showed a porous biomimetic scaffold with size that was approximately equal to the intrinsic porosity of the polymer under investigation (Fig. 8b). The bioactivity of the scaffold on neural stem cells, showed a rapid proliferation after 3 days (Fig. 8c).

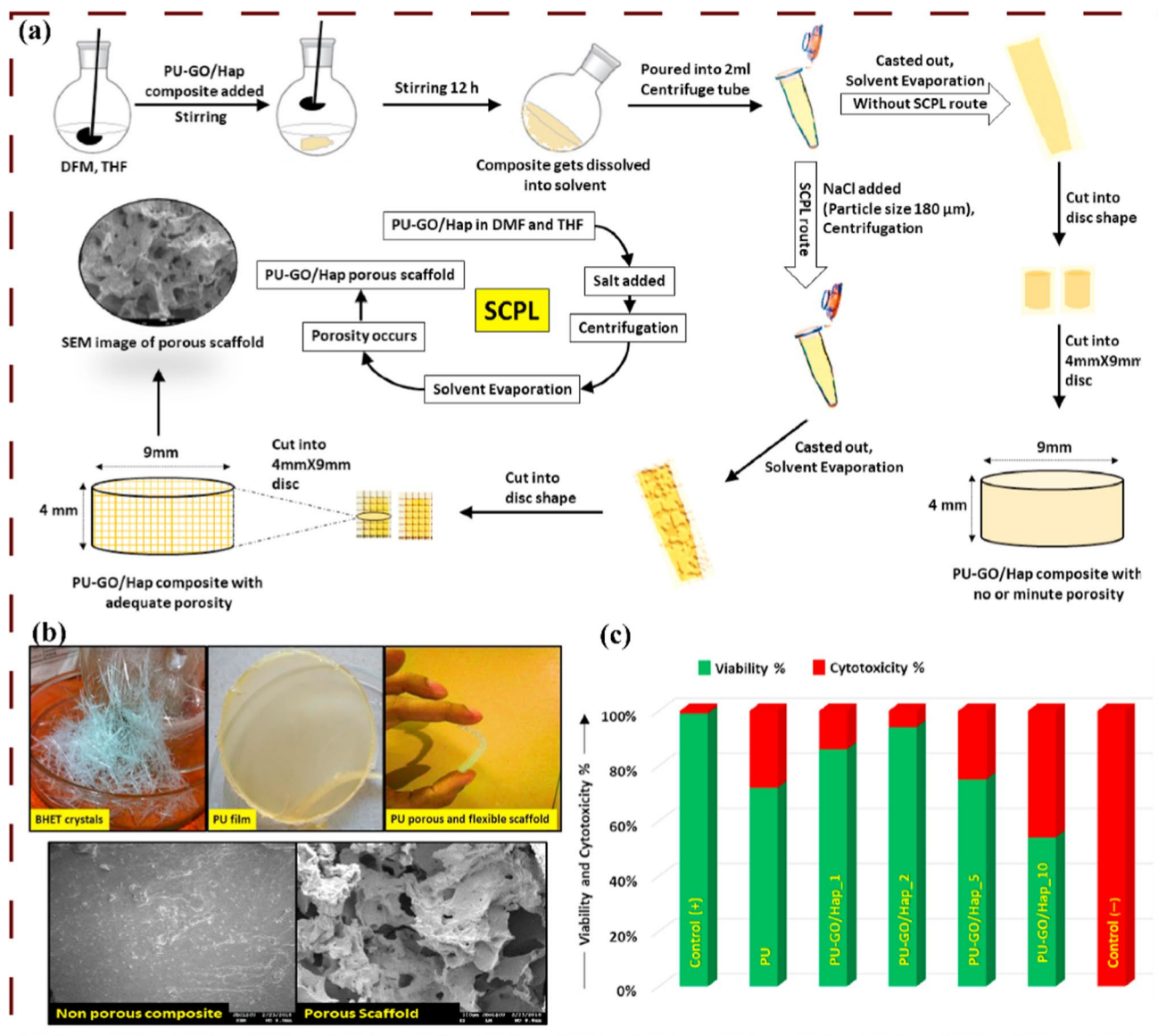


Fig. 7 Polyethylene-terephthalate/graphene/calcium-hydroxyapatite nanocomposite: **a** fabrication process, **b** scanning electron microscopy image and **c** cytotoxicity and cell viability investigation (Reproduced with permission from ref. [76]. Copyright 2020, Elsevier Ltd)

Mechanical strength is an essential property of biomimetic scaffold. By controlling the porosity of the polymer nanocomposite scaffold, the mechanical strength of the scaffold can also be manipulated for optimal and smart performances. It has been reported that biomimetic scaffold designed and fabricated without considering the native structures and properties of cells and natural tissue, would perform unsatisfactorily due to poor mechanical properties, wear, and corrosion [78]. A biomimetic scaffold should possess Young's modulus, elasticity, strength, and stiffness that are close to that of a typical natural bone. The porosity must be adequate and toxic-free.

In a summary of this section, it has been shown that biomimetic scaffolds, made of polymer nanocomposites can encounter impurities, non-homogenous morphology, hydrophobicity, and incomplete solubility of the nanoparticle challenges. An unoptimized concentration of the nanofillers in the polymer matrix is harmful to the mechanical and porosity properties of the scaffold. For instance, an excessive volume fraction of nanoparticles, e.g., graphene, carbon-nanotube, can cause excessive porosity in the polymer nanocomposite. Of course, excessive porosity is inversely proportional to the mechanical, and thermal properties of a polymer nanocomposite [79]. It is, therefore, very important that in conjunction with the

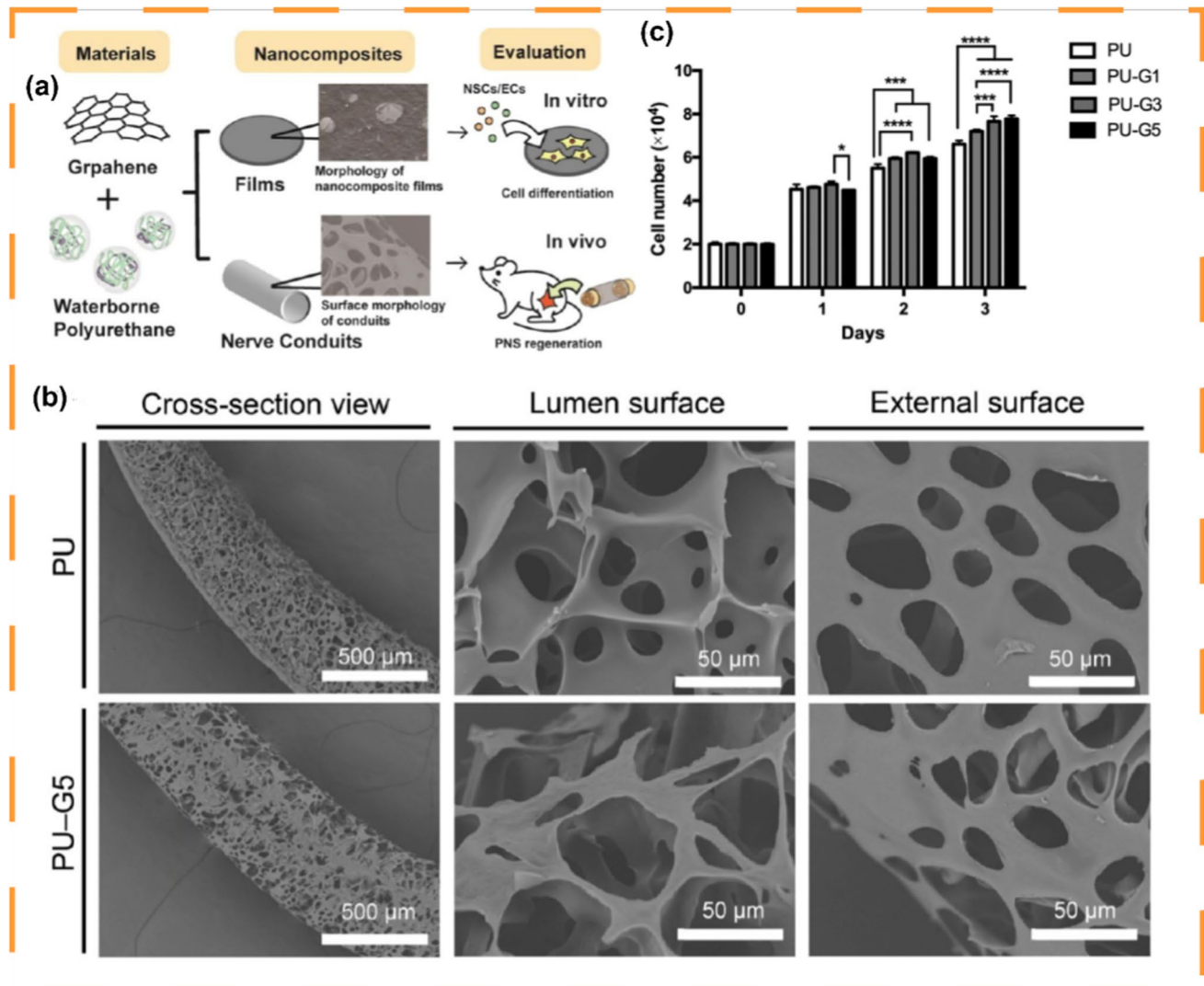


Fig. 8 Polyurethane/graphene nanocomposite scaffold: **a** fabrication process, **b** SEM images of nerve conduit and **c** bioactivity on neural stem cells proliferation (Reproduced with permission from ref. [77]. Copyright, 2019. American Chemical Society)

bioactivity properties of the polymer nanocomposite biomimetic scaffold, the relationship between the mechanical properties and porosity of the nanocomposites be established during the laboratory experimentation. The definition of high porosity must be clearly defined to know to what extent should biomimetic scaffold be porous. Cytotoxicity of the nanofiller must also be measured to ensure the cytocompatibility of the nanocomposite scaffold. The following points present the recaps for this section [80]:

1. The rate of degradation and the mechanical performance requirements, determine the porosity level of polymer nanocomposites biomimetic scaffolds.
2. Surface roughness can promote tissues/cells proliferation.

3. Pore size must be adequate with minimum size equal to 100 μm.
4. To maintain the correlation for an optimum performance of biomimetic scaffolds, the porosity, pore size, and mechanical properties must be substantially controlled by using suitable materials and fabrication techniques.

4 Polymer Nanocomposites for Aerospace Applications

Composite materials have been utilized in the aerospace industry since 1903, demonstrating their efficacy in the fabrication of both civilian and military aircraft parts [81]. The aerospace industry encompasses the aircraft and spacecraft industries. The various parts of the aerospace machinery

have been manufactured by using metals, fibre reinforced composites, and currently, polymer nanocomposites [82]. Polymer nanocomposites offer a myriad of benefits that have found new applications in aerospace engineering, primarily owing to the ability to tailor and manipulate the properties of polymers through the incorporation of nanofillers. Among the various considerations, the cost of air transportation is intricately linked to fuel expenses, which in turn, are directly proportional to the weight of the aircraft. The reduction in fuel consumption and the consequential low carbon emissions are economic advantages to the aerospace industries [83]. Therefore, the utilization of materials that are endowed with exceptional flexibility, optical ability, mechanical strength, thermal stability, and electrical conductivity, emerges as imperative in the manufacturing of aircraft components [84].

Amongst others, polymer nanocomposites are important materials for aircraft design owing to their strength-to-weight ratio, flexibility, and hardness [85]. The reduction in weight, minimization of corrosion problems, increased strength, flexibility, low cost, facile processing techniques, and high fatigue resistance advantages that can be derived from polymer nanocomposites, have made polymeric materials suitable for the manufacturing of aircraft parts. With these friendly advantages, the aerospace industries can possibly operate at reduced fuel consumption, reduced environmental pollution, and reduced noise pollution. Examples of polymers that are suitable for aerospace part manufacturing, include: polyurethane, polyether–ketone–ketone, polyether–ketone, epoxy, phenolic, polyimide, bismaleimide, polycarbonates, acrylonitrile butadiene styrene, polyamide, polyvinyl chloride, polypropylene, polyethylene–terephthalate, acrylonitrile styrene acrylate, and polyoxymethylene [86]. In addition, examples of nanofillers for aerospace part manufacturing, include: copper oxide, graphene, carbon nanotube, titanium dioxide, silicon dioxide, aluminum oxide, tin oxide, nano-clays, zinc oxide, and zirconium dioxide [82]. Table 2 presents the classifications of the materials that are suitable for aircraft parts fabrication.

During the fabrication of the structural parts of an aircraft comprising polymer nanocomposites, there abound defects,

which may occur because of the technological imperfections. Voids formation in the processed composite often poses a common challenge, since it can hamper the desired properties of the nanocomposites. The presence of voids leads to unwanted porosity, thereby diminishing the mechanical, thermal, and optical characteristics of the processed materials. The void is an imperfection in the structure of the processed composites, which are often introduced during the production process. High crystallinity can also affect the overall properties of the composites. Employing the appropriate processing techniques and ensuring the uniform distribution of fillers in the polymer matrix, are essential steps in mitigating the challenges associated with voids [86].

Several methods have been engaged to fabricate composites for aircraft structures; these production techniques are to ensure, over time, the cost friendliness, and the longevity of the structures. Based on the evidence from the literature [87–99], Table 3 presents the various aircraft structures production techniques, their merits, and demerits.

5 Conclusion

The applications of polymer nanocomposites in the electronic, biomedical, and aerospace industries, have been succinctly reviewed. The effects of defects in photovoltaic, biomimetic scaffold, and aircraft structure were discussed. Impurities introduced during the synthesis or processing stages can lead to irregularities in the material structure, which often affect its mechanical, electrical, biomedical, and optical properties. Similarly, a non-homogeneous mixture of organic and inorganic materials can result in uneven dispersion of nanoparticles within the polymer matrix, leading to localized regions of weakness or reduced performance. Additionally, incomplete solubility of nanoparticles in the polymer matrix can result in aggregation or phase separation, which can further exacerbate the formation of defects. The understanding and mitigating of these factors are crucial for the optimization of the properties and performance of polymer nanocomposites in various applications. An exploratory study on the effect of

Table 2 Polymer composites materials for aircraft structure fabrication

Thermoset	Thermoplastic	Nanoparticles
Polyurethane	Polyurethane	Carbon fibre
Epoxy	Polyether–ketone–ketone	Copper-oxide graphene
Phenolic	Polycarbonates	Carbon nanotube titanium dioxide
Polyimide	Acrylonitrile butadiene styrene (ABS)	Silicon dioxide
Bismaleimide	Polyamide (Nylon)	Aluminum oxide
	Polyvinyl chloride (PVC)	Tin oxide
	Polypropylene (PP)	Nano-clays
	Polyethylene terephthalate (PET)	Zinc-oxide
	Acrylonitrile styrene acrylate (ASA)	Zirconium dioxide
	Polyoxymethylene (POM)	

Table 3 Aircraft structures fabrication techniques, their merits, and demerits

Time	Techniques	Advantages	Disadvantages
Traditional	Hand lay-up	<ol style="list-style-type: none"> 1. Low cost due to inexpensive equipment 2. It can be used to produce complex shape structures 	<ol style="list-style-type: none"> 1. Reproducibility cannot be guaranteed. It depends on the skills of the operators 2. It requires rigorous labor
	Spray lay-up	The deposition rate is faster than that of hand lay-up technique	Fibre distribution in polymer matrices can be inconsistent
	Compression molding	<ol style="list-style-type: none"> 1. Low cost 2. When compared to the hand and spray lay-ups, the compression molding technique has a higher fabrication rate 3. Suitable for large-scale production 4. Suitable for producing materials with excellent properties 	<ol style="list-style-type: none"> 1. Complex tooling 2. High cost 3. Difficult to produce complex shapes and structures
	Injection molding	<ol style="list-style-type: none"> 1. Repeatability guaranteed 2. High precision 3. Suitable for large-scale production 	<ol style="list-style-type: none"> 1. The initial tooling and equipment are expensive 2. May require post-processing for surface finishing
	Vacuum bag processing	<ol style="list-style-type: none"> 1. Ability to produce large and complex parts 2. Flexibility 3. Defect and porosity free 4. Good surface finish 	<ol style="list-style-type: none"> 1. Labor-intensive 2. Long-cycle times 3. High cost of pump and other equipment
	Pultrusion	<ol style="list-style-type: none"> 1. Suitable for complex parts production 2. The production rate is high 3. Low cost when producing in large quantities 4. Continuous production 	<ol style="list-style-type: none"> 1. Little control over part shapes manipulations 2. Initial tooling cost is high
	Filament winding	<ol style="list-style-type: none"> 1. Light-weight material fabrication 2. High performance 3. Suitable for closed-cylindrical shapes 	<ol style="list-style-type: none"> 1. Inconsistent smooth surface of shafts 2. Postprocessing is required
	Powder metallurgy	<ol style="list-style-type: none"> 1. Suitable for large-scale production 2. High material strength 3. Complex part productions and precision can be achieved 	<ol style="list-style-type: none"> 1. Material selection and geometries 2. Variation in density 3. Not cost-effective
	Modern-day techniques	Resin transfer molding	<ol style="list-style-type: none"> 1. Low cost when producing in large quantity 2. Excellent finish of composite surface 3. Good nanofiller alignment Suitable for large-scale production
Vacuum-assisted resin transfer molding		<ol style="list-style-type: none"> 1. Inexpensive equipment and tools 2. Suitable for large-scale production 3. High production quality of composite parts 4. Good control of fibre-to-resin volume ratio 	<ol style="list-style-type: none"> 1. Process defects 2. Long-filling times 3. Labor-intensive 4. Complex tooling and setup
Coating		<ol style="list-style-type: none"> 1. The deposition rate and efficiencies are high 2. Suitable for complex parts production 3. It can increase corrosion and wear resistance of composites 4. Low cost 5. Flexibility 	<ol style="list-style-type: none"> 1. Fabricated composites are prone to crack, delamination, distortion, and contamination 2. Uniformity and thickness control may not be guaranteed

Table 3 (continued)

Time	Techniques	Advantages	Disadvantages
	Single screw extrusion	<ol style="list-style-type: none"> 1. Ruggedity, low-cost, and simplicity/flexibility 2. Effective in the melt processing of polymers 3. Suitable for large-scale production 	<ol style="list-style-type: none"> 1. Materials selectivity 2. Non-uniform mixing 3. Overheating 4. Geometric handling limitation
	Cross-accumulative roll bonding	<ol style="list-style-type: none"> 1. Suitable for producing high strength and good elongation composites 2. Uniform mixing and particle distribution 3. Low cost 	<ol style="list-style-type: none"> 1. Reduction in the bond strength due to individual particle inclusion 2. Surface defects due to repeated rolling 3. Not suitable for materials that are is susceptible to cracking
	Melt compounding	<ol style="list-style-type: none"> 1. Uniform dispersion of filler 2. Multi-application 3. Simplicity and low cost 4. Suitable for large-scale production 5. Easy scalability 	<ol style="list-style-type: none"> 1. Not suitable for heat-sensitive materials 2. High temperature can lead to the potential degradation of composites
	Vibrational casting	<ol style="list-style-type: none"> 1. Suitable for complex parts production 2. It can produce composites with good surface and low porosity 3. Uniformity of composites 4. It can produce composites with improved mechanical properties 	<ol style="list-style-type: none"> 1. Intensive labor 2. At higher vibration, porosity will be induced in the composites 3. Equipment complexity and limited application
	Ball mill fragmentation	<ol style="list-style-type: none"> 1. Control over composite morphology is possible 2. Versatility 3. Uniform mixing with high cohesiveness 4. Simplicity and ease of operation 5. Easy scalability 	<ol style="list-style-type: none"> 1. Dry milling only 2. Prone to contaminants
	Melt extrusion	<ol style="list-style-type: none"> 1. Can produce composites with high strength 2. Scalability and versatility 	<ol style="list-style-type: none"> 1. Multiple process steps 2. Not suitable for some materials and geometries
	Fused deposition modeling	<ol style="list-style-type: none"> 1. Simplicity and flexibility 2. Rapid prototyping 3. On-demand production 4. Simple control over matrix morphology 5. Suitable for polymer-based materials 	<ol style="list-style-type: none"> 1. The cost of producing high-strength material is high 2. Low mechanical strength of printed layers 3. Low printing speed and slow production rate 4. Poor surface finish and resolution 5. Shrinkage of model materials
	Hot filament chemical vapor deposition	<ol style="list-style-type: none"> 1. Inexpensive equipment 2. Homogenous deposition 3. Easy control over deposition conditions 4. Scalability and high rate of deposition 	<ol style="list-style-type: none"> 1. Complex equipment 2. Cost and safety concerns 3. Contamination
	Stir casting	<ol style="list-style-type: none"> 1. Suitable for producing composites with excellent mechanical properties 2. Economical for producing composites 	<ol style="list-style-type: none"> 1. Non-uniform distribution/dispersion
	High frequency induction heat sintering	<ol style="list-style-type: none"> 1. High efficiency 2. Pollution free 3. Fast production rate 4. It can produce composite high-consolidated density 	<ol style="list-style-type: none"> 1. Cost 2. Complexity of equipment 3. Not suitable for complex shapes

Table 3 (continued)

Time	Techniques	Advantages	Disadvantages
	Ultrasonication process	<ol style="list-style-type: none"> 1. Suitable for large-scale production 2. Simplicity 3. It enhances the polymerization rate 4. Scalability and uniformity of composites 	<ol style="list-style-type: none"> 1. Vibration can lead to thermal energy 2. Quality composites may not be guaranteed 3. Cost of equipment
	Vacuum and argon sintering	<ol style="list-style-type: none"> 1. Suitable for large-scale production 2. Simple process control 3. Reduced contamination 4. Suitable for producing composites with excellent mechanical properties 	<ol style="list-style-type: none"> 1. Cost of equipment 2. Long processing time 3. Not suitable for some materials
	Chemical vapor deposition	<ol style="list-style-type: none"> 1. It can produce highly dense and pure composites 2. Uniform mixture of composite materials 3. Suitable for producing complex shapes and scalability 4. Adjustable deposition rate 	<ol style="list-style-type: none"> 1. Use of toxic and hazardous chemicals 2. Deposition at high temperature 3. Complexity and cost problems 4. High cost of production
	Physical vapor deposition	<ol style="list-style-type: none"> 1. Environmentally benign 2. Suitable for many materials processing 3. Good properties of produced composites 4. Suitable for both organic and inorganic materials 	<ol style="list-style-type: none"> 1. Complex production processes 2. Not suitable for complex shapes 3. Low output and high production cost
	Spark plasma sintering	<ol style="list-style-type: none"> 1. Suitable for producing composites with excellent mechanical properties 2. The sintering time is short 3. High sintering heating rate 4. High efficiency 5. Versatility and wide range of applications 6. Fast cooling-rates 	<ol style="list-style-type: none"> 1. Not suitable for complex shapes and geometries 2. Cost of equipment 3. Complex process control 4. Not suitable for some materials

Table 3 (continued)

Time	Techniques	Advantages	Disadvantages
Most recent techniques	Solution-induced intercalation	1. Better dispersion of fillers in polymer matrices	1. High emission of organic solvent into the atmosphere
	Co-deposition	1. Uniformity of mixture 2. Enhanced properties of composite materials 3. High-rate deposition 4. Production of excellent composites mechanical properties	1. Cost of equipment and complexity 2. Material selectivity/limitation
	Selective laser melting	1. Accuracy, low production cost, and high precision 2. Production of composites with high and desirable mechanical properties 3. Suitable for producing composites with complex geometries 4. Reduced production time 5. Scalability and versatility 6. Suitable for large-scale production	1. Cost of equipment 2. Need for post-processing 3. Prone to surface roughness
	Electric field induced alignment	1. Simplicity and efficiency	1. Dimensional scalability restriction, due to ultrahigh-electric field strength requirement 2. A highly viscous filler will experience significant resistance in response to electric field 3. Reorientation of entangled fillers by electric field may be impossible 4. Formation of agglomeration and the non-uniformity of filler distribution 5. Material limitation due to an electrically conductive material requirement
	Magnetic field induced alignment	1. Scalability 2. Efficient orientation of fillers 3. Suitable for composites with excellent mechanical properties production 4. Multi-material printing	1. Ferromagnetic materials are only possible with magnetic field induced alignment 2. Complex equipment
	Ultrasonic cavitation	1. Uniform dispersion of fillers 2. Rapid heating and cooling rates 3. Fine/reduced particle size	1. Cost of equipment 2. Possibility of ultrasonic cavitations collapse, which can lead to substrate damage and erosion pits
	Electrospray deposition	1. Simplicity, flexible production process, and low energy 2. Particle size optimum control with low porosity 3. Room temperature operating condition 4. Suitable for quality and large-scale production 5. Scalability and low cost	1. Instability of spray droplets can result in structural deformity 2. Limited ionization rate 3. Complex equipment

defects of polymer nanocomposites in applications, such as: transistor, drug delivery, water purifier, and sensors, can further promote the industrial and commercial utilization of these versatile materials.

Acknowledgements The support of Tshwane University of Technology on this work, is highly appreciated by the authors.

Author contributions O.F. conceptualization, methodology, writing, and R.S., reviewed, edited, and supervised, and Y.H., and K.W. supervised.

Funding Open access funding provided by Tshwane University of Technology. This research was supported by Tshwane University of Technology, Pretoria 0001, South Africa.

Declarations

Conflict of Interest The authors declare no conflict of interest.

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